Closed Loop CNC Machining and Inspection of Interlinked Manufacturing Features for “Right First Time” Production

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ABSTRACT

Low rate production systems are severely affected by scrap especially if the raw material cost is high. The focus of this research is to address this problem by proposing a system to reduce scrap rate in machining of multi-feature products. The system entitled “CLosEd loop MAchining and inspecTIon System” CLeMatis achieves this goal by considering, for the first time, the sequence in which the features will be machined in conjunction with GD&T requirements that link the features together. During the manufacturing, after each step in the sequence, CLeMatis gathers data about features that are already machined for On-Machine Measurement (OMM) and updates coordinates of subsequent features that are yet to be machined to meet GD&T requirements where possible. CLeMatis thus aims to produce each part right first time. In order to validate the system, different scenarios are proposed to assess the capability of the system towards complex parts.

Keywords: CNC Machining, Inspection, Tolerances, On Machine Measurement.

1. INTRODUCTION

Most products consist of multiple assembled parts, and fitting parts together presents one of the major challenges especially for complex products. Design engineers interlink features to each other by specifying GD&T relations between features in order to ensure proper fit of parts. There are different types of errors that can take place in the manufacturing process, and to minimize the effect of these errors some constraints, in the case of machined parts, are added to the product design. Each feature’s dimension has two types of constraints: allowance and tolerance. Currently checking these GD&T requirements takes place when machining is completed. A large amount of literature has been carried out on stack tolerances research and its effect on the final product.

The aim of this research is to machine parts that are used in an assembly with interlinked features right first time. A closed loop error compensation system is proposed in this paper. This paper is divided into 7 major sections, with first introducing the research overview followed by a review of previous work in this field. The major sections provide a brief explanation of the proposed system and its methodology. A case study is presented to show the idea, and results discussed. Finally, the conclusion and future work are outlined.

2. REVIEW OF MACHINING AND INSPECTION

Product functionality, inter-changeability and manufacturability can be controlled by specifying the dimensional and geometric tolerances which directly affect the quality and cost of the product [1]. Dimensioning and Tolerance standards were introduced by the American National Standards Institute (ANSI) in 1982 and after then revised by the American Society of Mechanical Engineers (ASME) in 1994 (ASME Y14.5M 1994) which categorized the tolerances into six classes: (Size, Form, Orientation, Position, Profile, and Run out). Designers have to add tolerance zones to the actual size in order to cover up the dimensional variation through the manufacturing process to suit the assembly process with other parts.[2, 3]. Inspection is used to measure the dimensions of the components to identify these dimensions are within a specified tolerance. According to the British Standards Institution (BSi) tolerances are defined as “the total amount of variation permitted for the size of a dimension, a positional relationship or the form of a profile or other design requirements”[2].

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There are various causes of machining errors figured out in many works of research. Researchers [4] classified the cause of machining errors into two categories: *Machining accuracy related* and *tool accuracy related*, the machining accuracy is concerned with the accuracy of the tool path and consists of two types of errors: Quasi- static errors which relate to the machine structure and design, and dynamic errors which relate to the machine's moving elements. The tool accuracy is concerned with the workpiece fixturing and cutting tool errors. Other research defined the machining errors into *individual feature errors* and *combined feature errors* [5]. The individual feature errors can be resulted from cutting tool errors, miscellaneous errors, or programming errors. The combined feature errors can be resulted from fixture/work holding errors, miscellaneous errors, or machine tool errors. Figure 1 describes these errors briefly.

Bagshaw and Newman [1,5] have defined an integrated inspection system outlined in a Production Data Analysis framework. This involves the creation of feature based part model geometry, an operation plan and then creating an inspection procedure, automatic feature tolerance analysis and expert system to analyze the reason for any errors. Another model to solve the deterministic metrology problem for platform-type machine tools (PTMT) was developed [6]. The approach was based on normal deviations of the actual points of machined surface from nominal surface points. Accuracy of cumulative errors, cyclic deviations, backlash etc., was formulated. The error modeling was achieved for determining accuracy using typical setups in milling cylinders and planes. However the research in developing this model was purely analytical and limited to simple cylindrical features and planes.

Henke [7] proposed two models representing form errors in cylindrical features to highlight the relationships between manufacturing process variables and deviations from perfect geometric forms. Ramesh [8] presented a model for error compensation in CNC machine tool elements. Finite element techniques were used to model and analyze thermal and kinematic errors due to extended usage of the machine. The usage of a machine tool produced thermal expansion in its various structural elements. The proposed model however did not give an entirely accurate picture of the total errors in the machine tool structural elements as the errors were determined through Finite Element Modelling (FEM) techniques which gave an approximation in results.

A method for machined surface error compensation was introduced by Myeong [8]. It was based on an inspection database which used an on-machine measurement system in profile milling. The geometric error compensation of the machining center was achieved by using a closed-loop configuration and the probing errors were also considered. A workpiece was machined and then inspected for surface error distribution. In order to efficiently analyze the surface errors, two characteristic surface error parameters Werr and Derr were defined. Various polynomial functions for determining surfaces error were used and experimentation was carried out to validate it [9]. Similar work by Yann [10] was used to predict the influence of cutting forces on the machine spindle deformation or any fixture or holding deformation. Taking the positioning error into account, the inaccuracies for side milling as well as end milling were modeled from the cutting conditions used. These models were used to predict machining errors specific to the machining type and compensated in relation for them.

A machining error compensation method using polynomial neural network (PNN) was presented by Cho et.al. [11], based on machining error estimation, an iterative computational algorithm has been used in order to correct the tool path by repeatedly shifting the tool positions. A geometric algorithm has been used on complex tolerancing problems in order to optimize the impact of tolerances specification on manufacturing cost.[12].

Another methodology was introduced to improve the machining accuracy using a parametric model, although the On Machine Measurement (OMM) system is used to inspect the machined parts on the machining center but the inspection process takes place after machining processes end and all the error compensations are uploaded to the CNC machine controller for further machining [13]. A systematic method was introduced by Kono [14] to model and compensate geometric errors to improve the flatness of the workpiece. Although this research is valuable but it does not deal with all errors and does not compensate the errors during the process.

It can be concluded from the literature that although the closed loop systems provide a solution to overcome machining errors, all error compensation takes place after machining the part and all updates applied on the further products. That means if there is an assembly products that require high precision the probability of rejecting these parts is high. The problem can go beyond this stage if the part material is expensive such as Titanium or Cobalt Chrome.

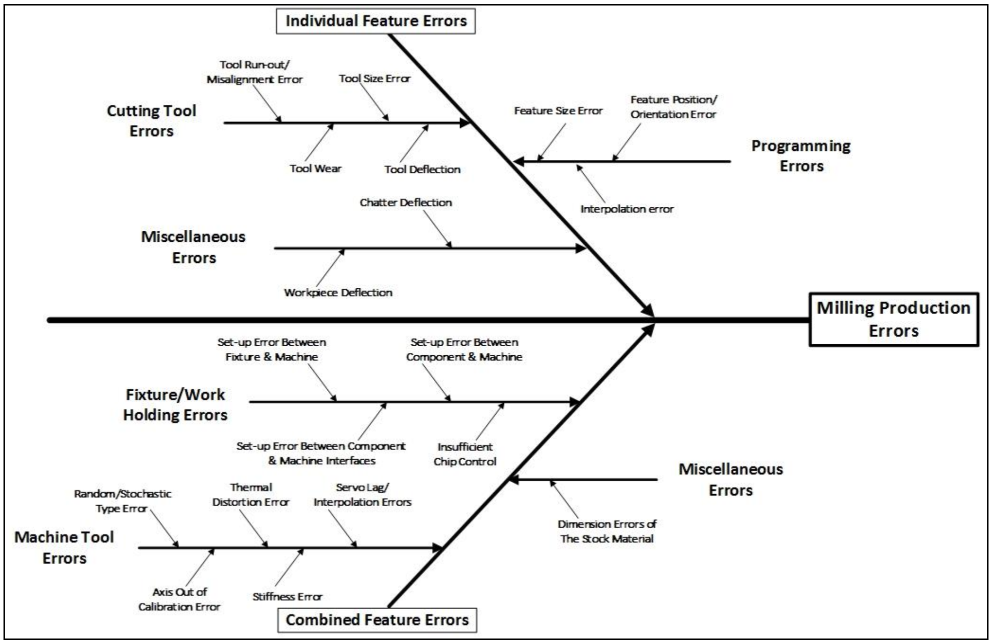

Figure 1 Machining errors causes

3. Closed Loop CNC Machining and Inspection of Interlinked Manufacturing Features

This paper starts to investigate a practical solution to minimize the features machining errors and compensate the deviations online during the process. The Closed Loop CNC Machining and Inspection System (*CLeMatis*) proposed in this paper provides a solution for the problem defined earlier in section 2. At this section the methodology of the system is explained with all its features and mechanism.

3.1. Methodology

The proposed methodology consists of the systematic steps in order to compensate the machining errors for interlinked manufacturing features. In this paper the feature parameters are updated manually. Automation of this system is still under investigation. First, all parameters for the workpiece and features must be defined such as co-ordinates, datums, dimensions, tolerances, positioning, features relationship constraints. These definitions can be defined by operator or extracted directly from the CAD or CAM file.

The proposed methodology shown in figure 2 is a closed loop system with all machining and inspection processes taking place on a single CNC milling machine. The first step starts by measuring the workpiece and calculates its deviation to ensure that it falls within tolerance and whether it needs further machining or not. Secondly, specifying the first feature to be measured which is already defined earlier. Most of the time this feature will be related to one or more of the workpiece parameters. The first feature's machining co-ordinates will be updated accordingly to the calculated workpiece deviation. After machining the feature; it goes through the inspection process to calculate its deviation and to check whether it falls within its tolerance or not, if "yes" the next feature go through the same process after updating its co-ordinates depending on the deviation of the machined predecessor feature, if "not" either re-machine the feature or reject the whole part.

3.2. Defining Predecessor Feature

A critical factor in the production of precision components is the dimensional and positional accuracy of features on a manufactured component. In this research the mechanism of defining the features relationship and how these deviations affect the other manufacturing features is the major issue in terms of their machining co-ordinates. Figure 3 shows a simple example how the system differentiates between the features deviations and which deviation affects which feature. The idea has been taken from the critical path method used in the operations research to define the predecessor feature instead of the predecessor task. The example shows that there are five features to be machined

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on the workpiece and presented in circles, and there are relations between these features demonstrated by the arrows. The example shows features “1” and “2” are dependent on the workpiece which means that any deviation in the workpiece will affect the first two features directly. Features “4” and “5” as the same as features “1” and “2” but this time they depend on features “2” and “3” respectively. Feature “3” has two constraints as it depends on features “1” and “2” together, that means that there will be a combined deviation from feature “1” and “2” has to be considered and calculated in order to update the machining co-ordinates for feature ”3”. Concluding, each feature will be updated only according to its predecessor feature.

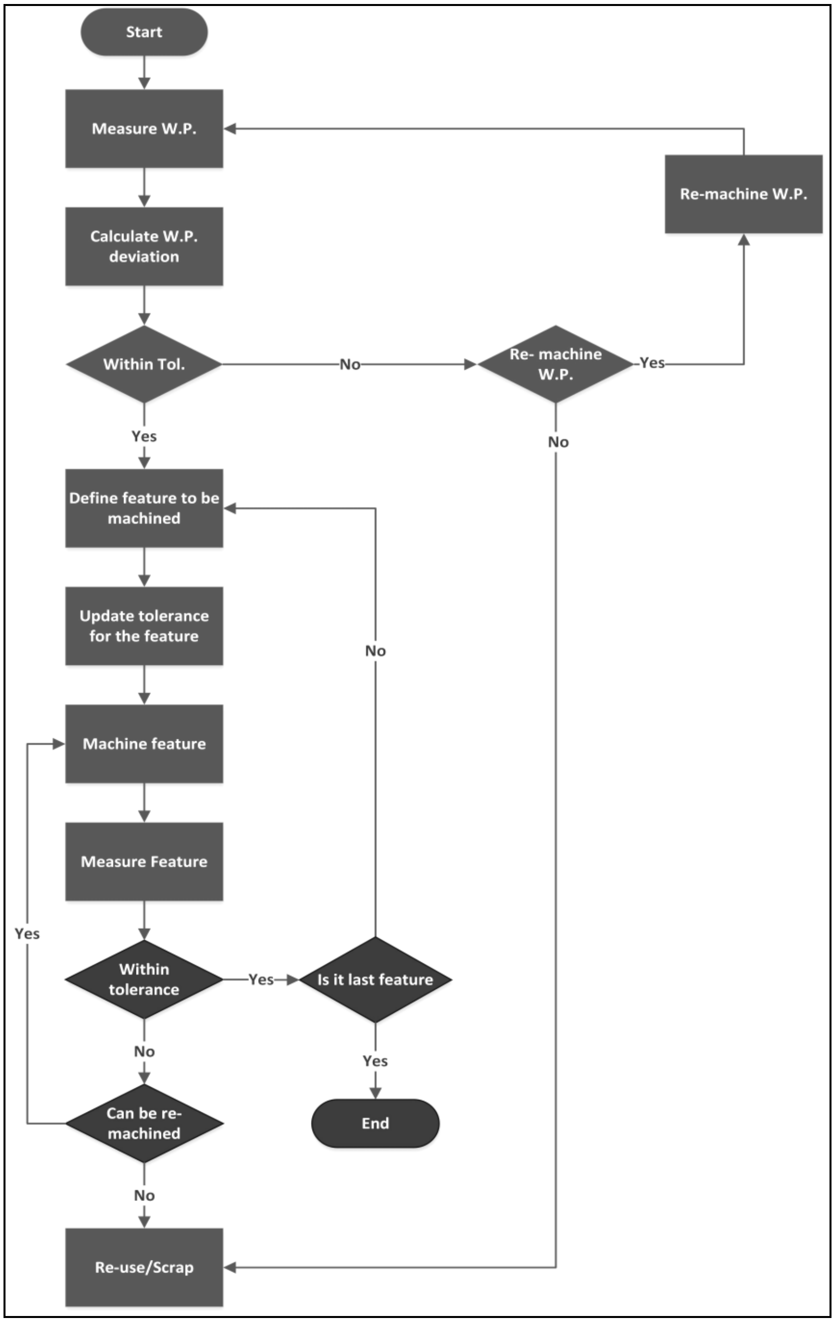

Figure 2 Closed loop for machining and inspection flow chart

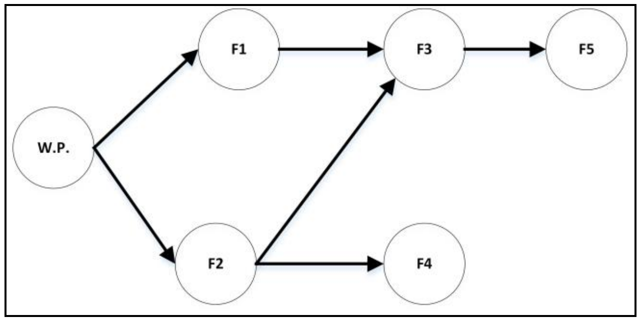

Figure 3 An example shows the relationship between features

3.3. CALCULATING FEATURES TOLERANCE

As mentioned before in the *CLeMatis* system mechanism, each feature tolerance has to be updated according to its predecessor feature deviation. So, simple mathematical equations have been developed using an Excel spread sheet. First some parameters have been defined as follows: “μ_i” is the mean for a specific feature’s dimension where “i” represents the number of the updated constraints. “UCL” and “LCL” are the upper and lower control limits for a specific dimension.

For example if there is a hole with 10 mm diameter and its center co-ordinates are [x = 50 ±0.05 mm and y = 25 ±0.05 mm], that means μ_1= 50 mm, UCL= 50.05 mm, LCL= 49.95 mm. After machining the predecessor feature, it was found that there is an error of (-0.01 mm) in the direction of X co-ordinate. If this value is added to the dimension of the feature to be machined the μ value will be [μ_1+ (-0.01) = 50 - 0.01 = 49.99 ± 0.05] which is not accurate because if the feature has been machined and its deviation was (-0.05) which means that μ = (49.99 – 0.05) = 49.94 mm. this means that although the feature dimension is still within tolerance but it failed to fulfill the nominal geometric tolerance constraint.

To overcome this problem both tolerances must be considered. Figure 4 shows the tolerance zones for a specific feature dimension in which μ_1, UCL_1, LCL_1 represent the nominal geometric tolerance zone, while μ_2, UCL_2, LCL_2 represent the updated geometric tolerance zone after adding the deviation error. When adding both zones to each other, there will be a common area between them which is the new tolerance zone for the required feature in which μ_3, UCL_3, LCL_3 are the mean, upper, and lower control limits respectively.

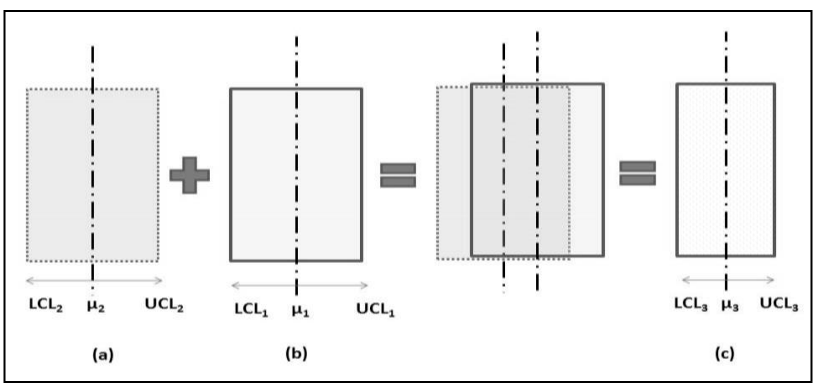

Figure 4 Schematic drawing shows different tolerance zones and their common area
(a) tolerance zone with deviation error, (b) nominal tolerance zone, (c) the new updated tolerance zone

To calculate the new dimension and tolerance for this example shown in figure 3; simple equations have been used as follow:

$$UCL_3 = \min(UCL_1, UCL_2)$$

$$LCL_3 = \max(LCL_1, LCL_2)$$

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$$\mu_3 = (\mu_1 + \mu_2) / 2 \quad \textbf{OR} \quad \mu_3 = (UCL_3 + LCL_3) / 2$$

So the general equation will be as follow:

$$UCL_{new} = \min (UCL_1, UCL_2, ..., UCL_i)$$

$$LCL_{new} = \max (LCL_1, LCL_2, \ldots, LCL_i)$$

$$\mu_3 = (UCL_{new} + LCL_{new}) / 2$$

3.4. ERROR COMPENSATION PROCESS

After calculating the new mean and tolerance zone for a feature, the values will be updated to the machining routines through the CNC controller. These updates as mentioned previously, will take place either manually or automatically. The updated feature will be machined after then, after machining it will go through the measuring process to measure the deviation. The same steps will be repeated again for all features on a part.

4. CASE STUDY

An example workpiece according to ISO 14649 – 11[15] has been taken to test the proposed methodology as shown in figure 5. The workpiece contains a pocket and a hole, all features parameters have been defined as shown in figure 6 in which the center co-ordinates for the workpiece, hole, and pocket were defined as well as tolerances and the predecessor features. Assumptions had been made for the predecessor features and tolerances in order to verify the system.

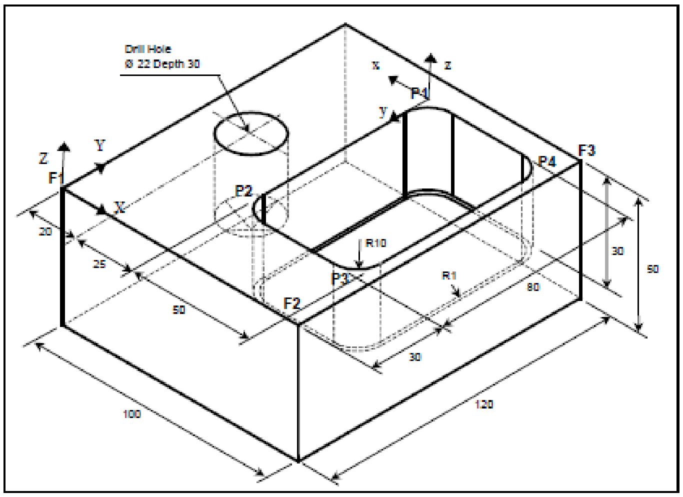

Figure 5 The ISO 14649 – 11 workpiece example [14]

Excel spread sheet was used to simulate the proposed system *CLeMatis* using the developed equations. According to previous research work, done by Sanjeev[16], data for machining features has been collected and analyzed in order to define the error distribution of it. The data collected was for 10 parts each contains 4 holes, and after measuring all these features the data went through the test of normality using the histogram and it was concluded that they are normally distributed. The *CLeMatis* uses the normal distribution to generate random numbers for the actual dimension for the simulation.

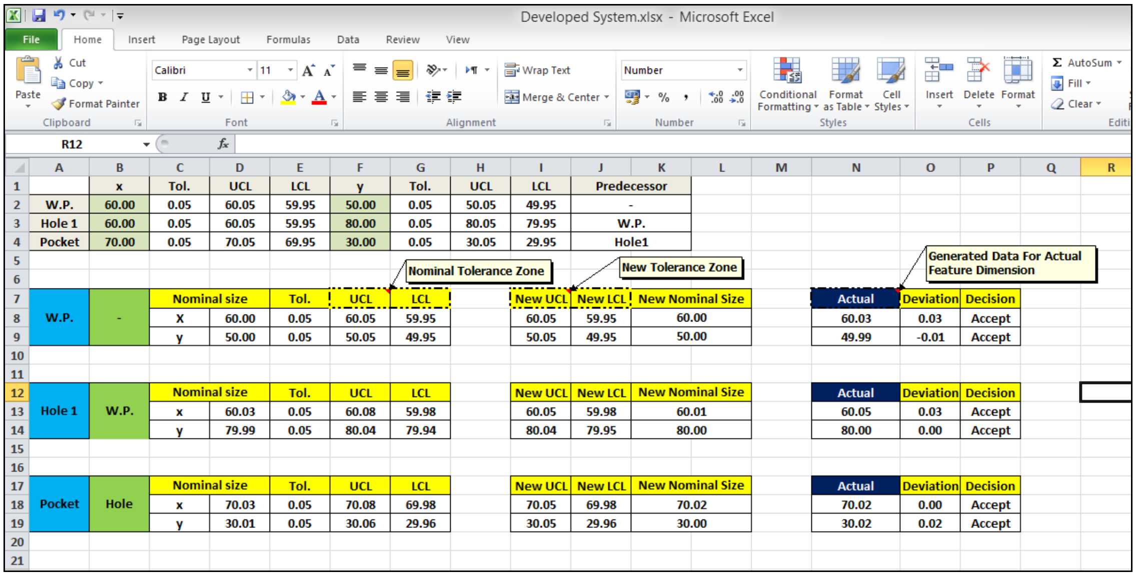

Figure 6 Screenshot for the data sheet used to simulate different scenarios

5. RESULTS

The system simulation shows that the nominal coordinates and tolerance for each feature were updated automatically according to its relationship with other features. The new coordinates were calculated using the equations discussed earlier in section 3.3. All data for the actual features coordinates had been generated according to the normal distribution and it was found that all of them fall within the new tolerance zone as shown in figure 6. Also, it is recognized that the new tolerance zone for each feature is smaller than the nominal tolerance zone, e.g. for the hole, its nominal tolerance was ±0.05 decreased after then to ±0.035, and the same values for the pocket.

The simulation results prove the theoretical model discussed earlier in section 3.3 which describes the decreasing trend of the feature tolerance zone each time when adding more constraints. This decreasing in the tolerance zone means that at some point the feature cannot be machined because the CNC machine capability will not be able to achieve this narrow tolerance zone. It can be concluded that the capability of the proposed system to deal with different scenarios does not depend on the number of constraints as much as it depends on the feature new tolerance zone results from these constraints with respect to the CNC machine capabilities.

These results prove the theoretical model for machining linked features right first time, but it still not validated until practical experiments take place with different scenarios for more complex products and more linked features, the results came out of these experiments will help in defining the minimum tolerance zone, which can be called "The Pivot Zone", that can be accepted by the developed system "*CLeMatis*". As a conclusion, if the machine precision is greater than the pivot zone, then the machine will not be able to meet the recognised updated parameters of the feature to be machined and tends to reject the whole part.

6. CONCLUSIONS

This research provides an investigation to overcome the problem of machining error for assembly parts. A closed loop CNC machining and inspection system entitled *CLeMatis* was proposed. *CLeMatis* has the ability to interlink the features to be machined, determining and updating the co-ordinates and tolerances of features online during process. *CLeMatis* provides an optimization of the feature deviations compensation. A case study proposed in order to assess the capability of the system towards assembly parts, and the updating had been done manually. The system used an Excel spreadsheet to simulate the compensation process and shows that it is applicable to update features parameters online during process. This paper is considered as the first step in the establishment of an adaptable system of right first time part production. The system will play as a main tool in the advanced manufacturing

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systems and help them to compete for high quality products and shortening production cost especially for assembly parts and machining of high cost materials.

7. FUTURE WORK

More investigation are now taking place to automate the system and adapt it to a standard mainly STEP-NC standard (ISO 14649) in which the CAM file will contain the machining and inspection routines and has the ability to update these routines automatically without any need to the operator. Also, more updates will take place in order to make *CLeMatis* capable to deal with more complex parts and more interlinked features.

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